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AFSWP - 970
October 1956

TREE BREAKAGE CHARACTERISTICS UNDER STATIC LOADING OF SEVERAL HARDWOOD SPECIES

DIVISION OF FIRE RESEARCH
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

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ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of W. Lai and F. M. Sauer in their helpful discussions concerning analytical procedures. G. D. Cooper, D. S. Dealey, and S. L. Krugman aided in data reduction.

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TREE BREAKAGE CHARACTERISTICS UNDER STATIC-LOADING OF SEVERAL HARDWOOD SPECIES

by

W. Y. Pong

Interim Technical Report
AFSWP-970
October 1956

U. S. Department of Agriculture
Forest Service
Division of Fire Research
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SUMMARY

An investigation was made to determine the energy necessary to cause breakage and uprooting of hardwood trees, and to determine the extent of damage that may occur in a hardwood forest at a given energy level. The analysis presented in this paper delineates essential parameters involved in breakage and uprooting of tree stems by a single load. These parameters provide a basis for the correlation of experimental data.

Twenty-four trees consisting of six species selected from a site II or better mixed-hardwood forest were tested under static loading. Quantitative measures of the force and deflection required to break and uproot these trees were recorded.

Static work modulus values were calculated by use of dimensionless parameters of force, deflection, and restoring force constant derived from the field data for each tree. The results are presented by plotting the actual frequency distributions of the static work moduli by species and type of failure, or both, as percent of cases occurring which are equal to or less than any chosen modulus value. The general level and magnitude of the frequency distributions were found to be approximately the same regardless of species or type of failure. Statistical tests indicate that all the trees tested are from the same population. Therefore, grouping of all static work modulus values into one frequency distribution appears to be justified.

Application of the results of this study should permit the prediction of the energy required to break or uproot any given tree in a site II or better hardwood forest for any probability level. The extent of damage that this forest may sustain for a given energy level may also be predicted.

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INTRODUCTION

Wind damage in the form of fallen and broken trees has been studied in both conifer and hardwood forests. The damage was often very heavy and extensive. Anderson (1)[1/] reported damage in Scotland totaling more than 45 million cubic feet of timber after the storm of January 31, 1953. Clapp (5) and Curtis (6) estimated that between 3 and 4 billion board-feet of timber was windthrown in New England by the hurricane of September 21, 1938. Earlier studies of damage were reported by Behre (2), who gave an account of the blowdown in the Adirondacks after the windstorm of 1916, and Cajander (4), who studied the damage caused by a storm which struck Finland in 1933.

Despite the copious amount of literature pertaining to windfall and breakage of trees, very little progress has been made in quantitative determination of the force necessary to cause uprooting and breakage, and of the extent of damage associated with known forces. In his thorough investigation on New England hurricanes, Smith (15) attempted to classify 123 storms according to the intensity of damage which was known to be caused or may have been caused by these storms. Smith acknowledges the fact that the classification was unsatisfactory because of a lack of information on damage and variability in method with which wind velocities were recorded at different localities.

Sherlock et al (14) investigated the variation in strength of transmission poles in relation to the wind forces which act against them. They concluded that the distribution of the windload to the individual poles in the line depended on the relative flexural stiffness of the poles as well as the relative resistance to movement in the ground. Trees may be subjected to similar wind forces as poles, but the reactions of the trees to these forces are quite different because of differences in base fixity. Day (7) in his study on windthrow observed a definite rocking of the tree's root system before it was thrown.

The purpose of this study is to determine 1) the energy necessary to cause breakage and uprooting of hardwoods and 2) the extent of damage that may be expected in a hardwood stand when exposed to different levels of energy.

1/ Underlined numbers in parentheses refer to Literature Cited, page 43.

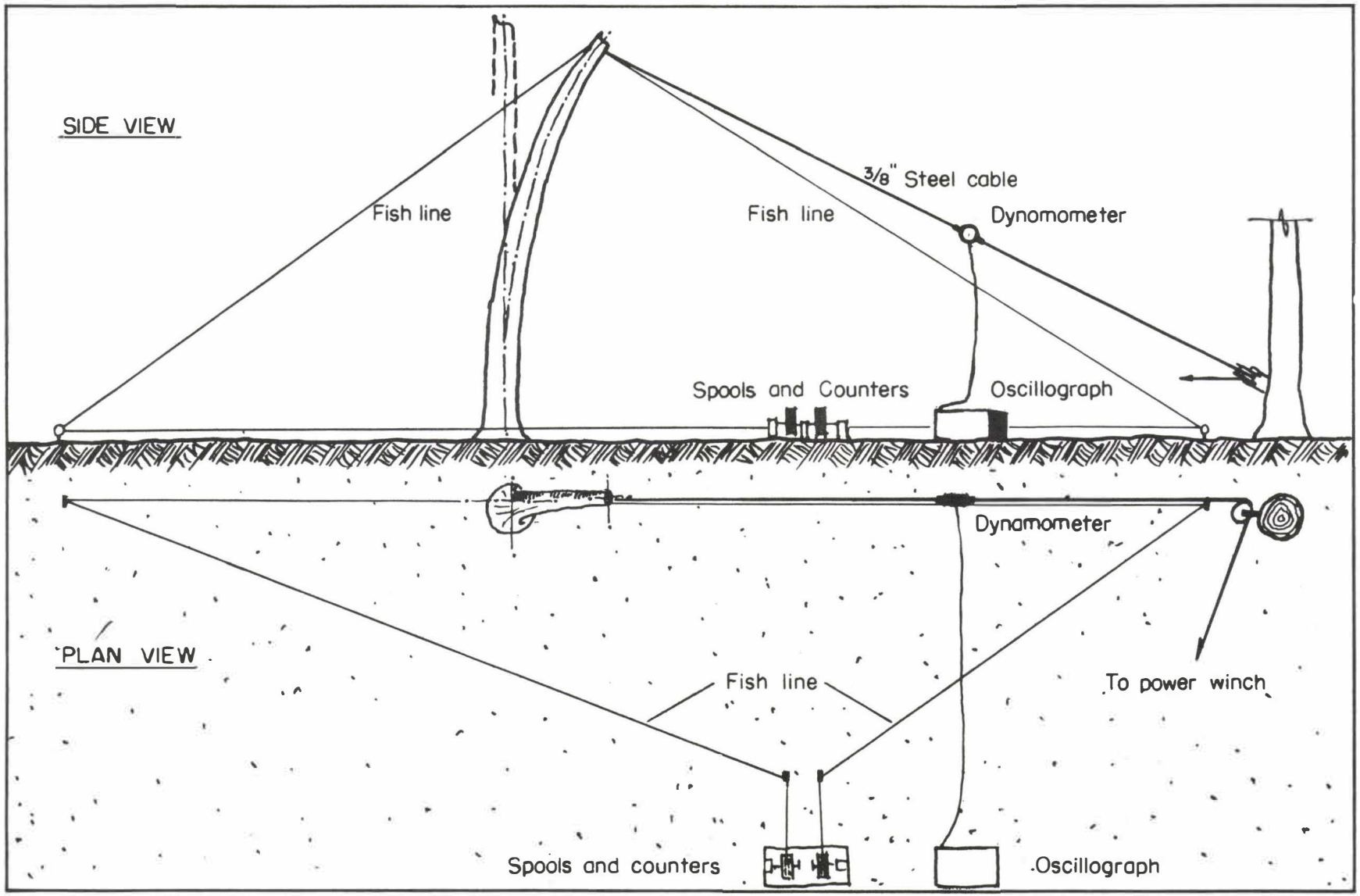

Figure 1.--Layout for static bending test

Loading was stopped at successive intervals of 3 to 4 feet deflection at which time the counters were read and the force recorded on the oscillograph. This procedure continued until the stem broke or uprooted (figures 4 and 5). From the series of counter readings, the deflection of the loading point could be plotted by triangulation for correspondingly measured loads.

Figure 4.--Typical tree stem break, TB-8, scarlet oak

Figure 5.--Uprooted tree stem, TA-38, sweet birch

After the stem failed, cuts were made at stump height,[4/] breast height, below and above the break when breakage occurred, and at convenient intervals along the remaining portion of the stem. Characteristics of the failure were recorded along with its position on the stem, and average diameters inside bark at each cut were measured for determination of form factor.

4/ Stump height is 1 foot above ground level.

Table 2.--Experimental stem breakage data[1/]

Column		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Tree No.	Species	Age (yrs)	H_o (ft)	H_{bh} (ft)	H_{cp} (ft)	d_{bh} (in.)	d_i (in.)	b	a	c	f_1	R_{eb} (lb)	y_b (ft)	k_a (lb/ft)	f_{br}
TA-14	Y.P.	33	69.1	64.6	39.0	6.1	5.5	.510	.590	.864	.404	253	37.2	10.2	.96
TA-29	Y.P.	32	77.8	73.3	41.5	8.3	7.8	.580	.500	1.160	.434	353	28.9	36.7	.84
TA-34	Y.P.	60	100.1	95.6	53.7	21.6	19.5	.545	.650	.838	.442	3,920	16.7	450.0	
TA-35	Y.P.	46	85.9	81.4	37.5	10.5	9.5	.555	.580	.957	.542	895	23.0	68.0	.97
TA-37	Y.P.	50	94.8	90.3	53.0	14.6	13.2	.660	.460	1.435	.420	1,367	26.0	72.9	.82
TA-23	S.B.	53	78.6	74.1	44.0	12.5	11.8	.560	.530	1.057	.406	2,062	16.6	183.6	.78
TA-31	S.B.	67	61.5	57.0	31.5	13.7	13.0	.850	.208	4.087	.451	3,142	12.6	608.8	
TA-38	S.B.	56	71.4	66.9	40.0	11.2	10.5	.632	.463	1.365	.402	1,273	23.3	138.0	
TA-39	S.B.	63	53.6	49.1	22.9	6.0	5.4	.668	.452	1.478	.534	383	20.2	63.0	
TA-44	A.B.	51	48.5	44.0	25.8	5.9	5.8	.665	.350	1.900	.414	524	21.1	38.0	.87
TA-45	A.B.	62	61.3	56.8	32.6	9.6	9.2	.685	.365	1.877	.426	1,208	19.1	103.6	
TA-22	P.H.	59	77.0	72.5	51.9	9.9	9.0	.520	.710	.732	.299	2,117	43.1	46.3	
TA-23	P.H.	52	59.3	54.8	30.8	7.9	7.0	.400	1.000	.400	.438	379	36.6	26.4	
TA-24	S.M.	58	62.7	58.2	35.3	14.0	13.0	.523	.587	.891	.399	2,812	19.7	325.0	
TA-8	S.O.	64	73.9	69.4	34.3	11.2	10.5	.525	.605	.868	.512	1,994	21.1	267.5	.88
TA-9	S.O.	64	82.1	77.6	52.1	14.3	13.2	.505	.600	.842	.329	2,395	21.8	327.5	.85
TB-1	S.O.	118	84.5	80.0	40.9	14.1	13.2	.410	.780	.526	.489	1,449	20.8	385.0	
TB-2	S.O.	62	79.9	75.4	43.0	11.9	11.1	.580	.520	1.115	.430	1,525	23.3	135.0	
TB-3	S.O.	60	70.6	66.1	30.4	8.2	8.1	.555	.555	1.000	.546	1,387	28.6	94.6	
TB-4	S.O.	61	71.2	66.7	39.4	10.9	10.0	.530	.575	.922	.441	1,115	39.4	76.7	
TB-5	S.O.	58	73.1	68.6	39.6	9.5	8.8	.385	.770	.500	.431	1,773	42.8	98.3	1.00
TB-6	S.O.	49	68.7	64.2	30.5	8.8	8.0	.400	.825	.485	.542	1,286	24.8	136.0	.95
TB-8	S.O.	67	69.8	65.3	38.3	12.1	10.0	.720	.505	1.426	.413	1,981	30.4	131.3	.89
TB-9	S.O.	58	79.3	74.8	45.9	13.8	12.5	.425	.940	.452	.386	3,320	34.2	162.9	.90

1/ Nomenclature given on page 45.

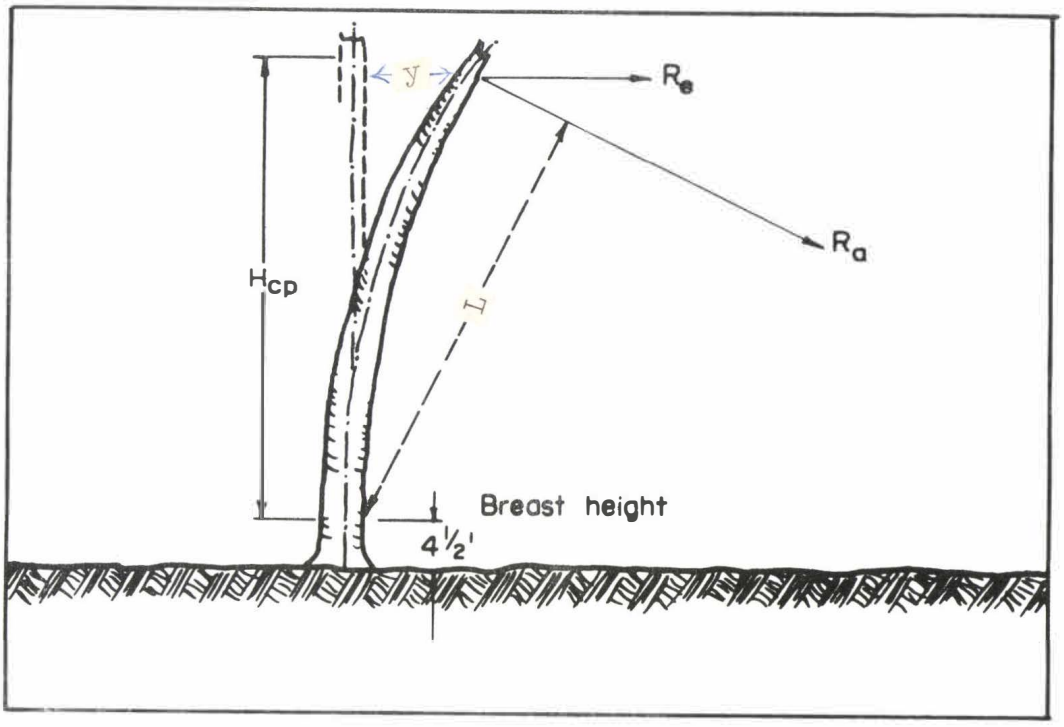

Figure 7.--Equivalent force $R_e = \frac{R_a L}{H_{cp}}$

Table 3.--Mechanical properties of green wood[1/]

Species	Modulus of Elasticity, E (lbs/sq.in.)	Modulus of Rupture, MR (lbs/sq.in.)	Reference Strain δ_r = MR/E x 10^6 (μ in./in.)[2/]
Yellow-poplar	1,090 x 10^3	5,400	4,930
Sweet birch	1,650 x 10^3	9,400	5,700
American beech	1,380 x 10^3	8,600	6,330
Pignut hickory	1,650 x 10^3	11,700	7,210
Silver maple	940 x 10^3	5,800	6,170
Scarlet oak	1,480 x 10^3	10,400	7,060

1/ From (11).

2/ Reference strain values are averaged calculated values for localities cited in the reference.

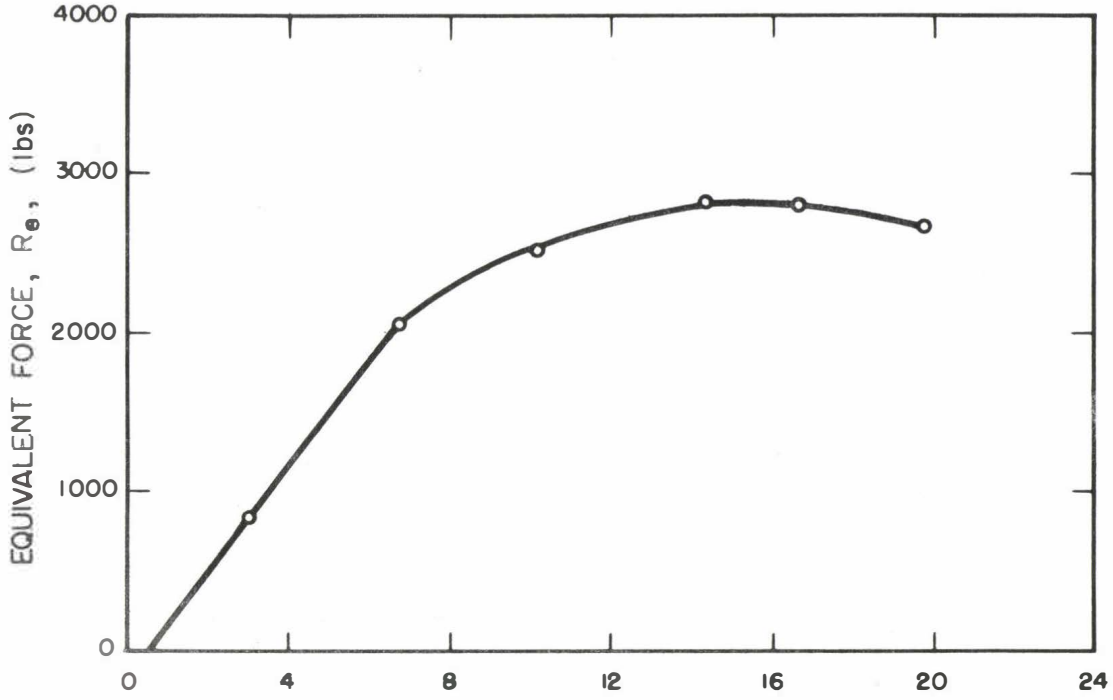

Figure 10.--Force-deflection curve for tree stem No. TA-24, silver maple--uproot

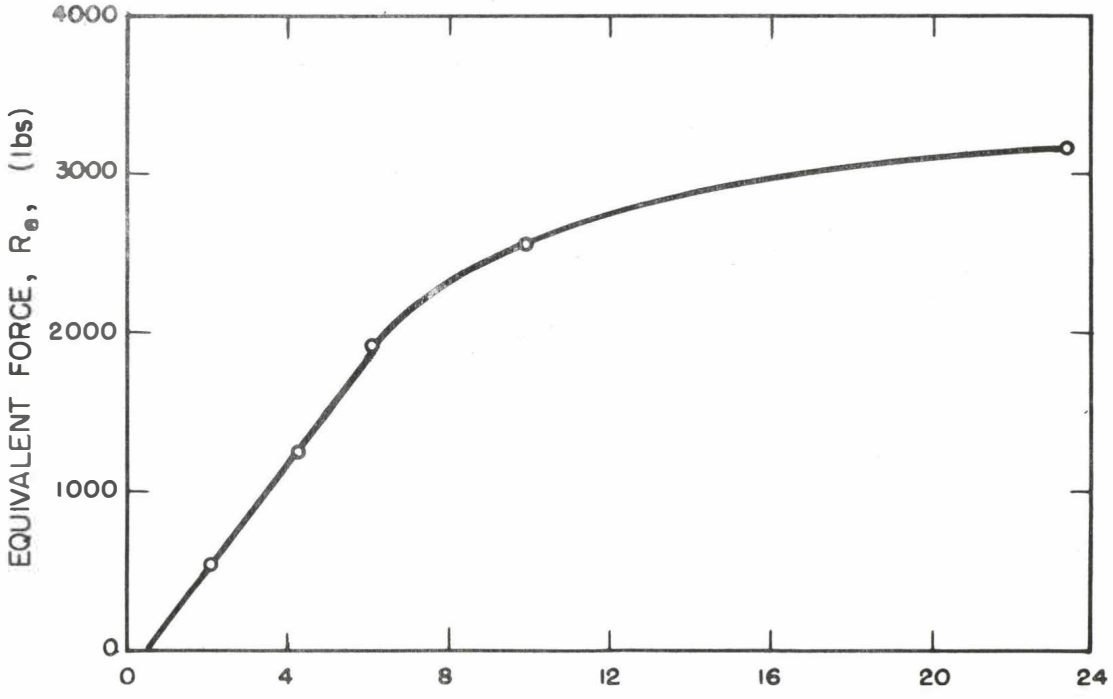

Figure 11.--Force-deflection curve for tree stem No. TA-38, sweet birch--uproot

Table 4.--Summary of static bending results on hardwoods

Species	Type		
	Break	Uproot	Total
Yellow-poplar	4	1	5
Sweet birch	1	3	4
American beech	1	1	2
Pignut hickory	0	2	2
Silver maple	0	1	1
Scarlet oak	6	4	10
Total	12	12	24

The theoretical restoring force constant, k_r, was determined from the equation

$$k_r = \frac{\bar{\beta}\ 3Ed_i^4\pi}{H_{bh}^3\ 64} \tag{3}$$

Values of $\bar{\beta}$, the restoring force function which contains the theoretical constant k_r, were obtained from a plot of the dimensionless expression

$$\frac{k_r\ H_{bh}^3\ 64}{3E\ \pi d_i^4} = \psi\ (c, f_1) \tag{4}$$

for applicable ranges of c and f_1 (figure 14). Dividing the actual restoring force constant, k_a (table 2) by k_r resulted in the dimensionless restoring force modulus, $\bar{K}$.

Stress along the stem was obtained from the equation

$$\frac{S}{S_{bh}} = \frac{(f - f_1)(f + c)^3}{(1 - f_1)(1 + c)^3 f^3} \tag{5}$$

where

$$S_{bh} = \frac{32R_{eb}\ H_{bh}}{\pi d_i^3}\ (1 - f_1) \tag{6}$$

Table 5.--Values of derived stem breakage parameters[1/]

Column		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Tree No.	Species	$\bar{\beta}$	k_r (lb/ft)	$\bar{K}$	S_m/S_{bh}	S_{bh} (lb/sq in.)	f_m	S_m (lb/sq in.)	S_{br} (lb/sq in.)	$\delta_{m/y}$ (in./in.) / in.	y_r (ft)	$\bar{Y}_b$	$\bar{R}_r$ (lb)	$\bar{R}_b$	$\bar{E}_b$
TA-14	Y.P.	3.172	11.97	.852	1.000	7,151	1.000	7,151	7,080	26.29	15.62	2.384	187	1.351	1.712
TA-29	Y.P.	3.613	37.97	.967	1.000	3,787	1.000	3,787	3,645	30.93	13.28	2.189	504	0.701	1.035
TA-34	Y.P.	3.993	736.78	.611	1.000	3,450	1.000	3,450	-	49.85	8.24	2.036	6,071	0.645	.957
TA-35	Y.P.	7.373	124.53	.546	1.000	473	1.000	473	463	50.73	8.10	2.839	1,009	0.887	1.965
TA-37	Y.P.	3.123	143.56	.508	1.001	3,825	0.932	3,829	3,787	30.94	13.28	1.954	1,906	0.717	.937
TA-23	S.B.	3.110	254.14	.722	1.000	6,749	1.000	6,749	6,409	41.34	11.49	1.443	2,920	0.706	.696
TA-31	S.B.	3.036	789.48	.711	1.154	5,478	0.745	6,300	-	80.70	5.89	2.135	4,650	0.676	1.153
TA-38	S.B.	2.843	194.74	.709	1.003	4,956	0.899	4,971	-	41.66	11.40	2.044	2,220	0.573	1.078
TA-39	S.B.	6.421	77.84	.809	1.000	6,800	1.000	6,800	-	69.87	6.80	2.972	529	0.725	1.920
TA-44	A.B.	2.841	53.69	.708	1.039	8,466	0.782	9,021	8,683	54.01	9.77	2.168	524	0.998	1.268
TA-45	A.B.	3.061	169.17	.612	1.030	6,183	0.816	6,368	-	53.75	9.82	1.945	1,660	0.727	.942
TA-22	P.H.	1.836	53.28	.869	1.000	18,051	1.000	18,051	-	23.44	25.63	1.683	1,366	1.550	1.146
TA-33	P.H.	4.489	109.79	.240	1.000	4,165	1.000	4,165	-	61.26	9.81	3.734	1,077	0.352	1.283
TA-24	S.M.	3.056	424.68	.765	1.000	5,493	1.000	5,493	-	74.10	6.94	2.838	2,947	0.945	1.999
TA-8	S.O.	6.430	353.88	.756	1.000	7,117	1.000	7,117	6,476	72.17	8.15	2.604	2,884	0.691	1.403
TA-9	S.O.	2.051	221.05	1.477	1.000	6,642	1.000	6,642	6,512	31.44	18.71	1.165	4,136	0.579	.645
TB-1	S.O.	5.998	538.40	.715	1.000	2,533	1.000	2,533	-	65.88	8.93	2.337	4,808	0.301	.641
TB-2	S.O.	3.523	189.24	.713	1.000	5,873	1.000	5,873	-	40.86	14.46	1.618	2,736	0.557	.628
TB-3	S.O.	7.481	169.14	.559	1.000	9,570	1.000	9,570	-	66.44	8.86	3.250	1,499	0.925	2.116
TB-4	S.O.	3.962	201.61	.380	1.000	5,089	1.000	5,089	-	54.79	10.74	3.682	2,165	0.515	1.774
TB-5	S.O.	4.192	117.81	.834	1.000	12,431	1.000	12,431	12,431	47.14	12.48	3.424	1,470	1.206	2.126
TB-6	S.O.	8.041	188.88	.720	1.000	8,989	1.000	8,989	8,401	77.24	7.62	3.263	1,439	0.894	2.086
TB-8	S.O.	3.157	170.66	.769	1.003	9,297	0.910	9,325	9,233	45.37	12.97	2.344	2,213	0.895	1.571
TB-9	S.O.	3.258	286.66	.568	1.000	9,544	1.000	9,544	8,920	46.53	12.64	2.714	3,625	0.916	1.475

1/ Nomenclature given on page 45.

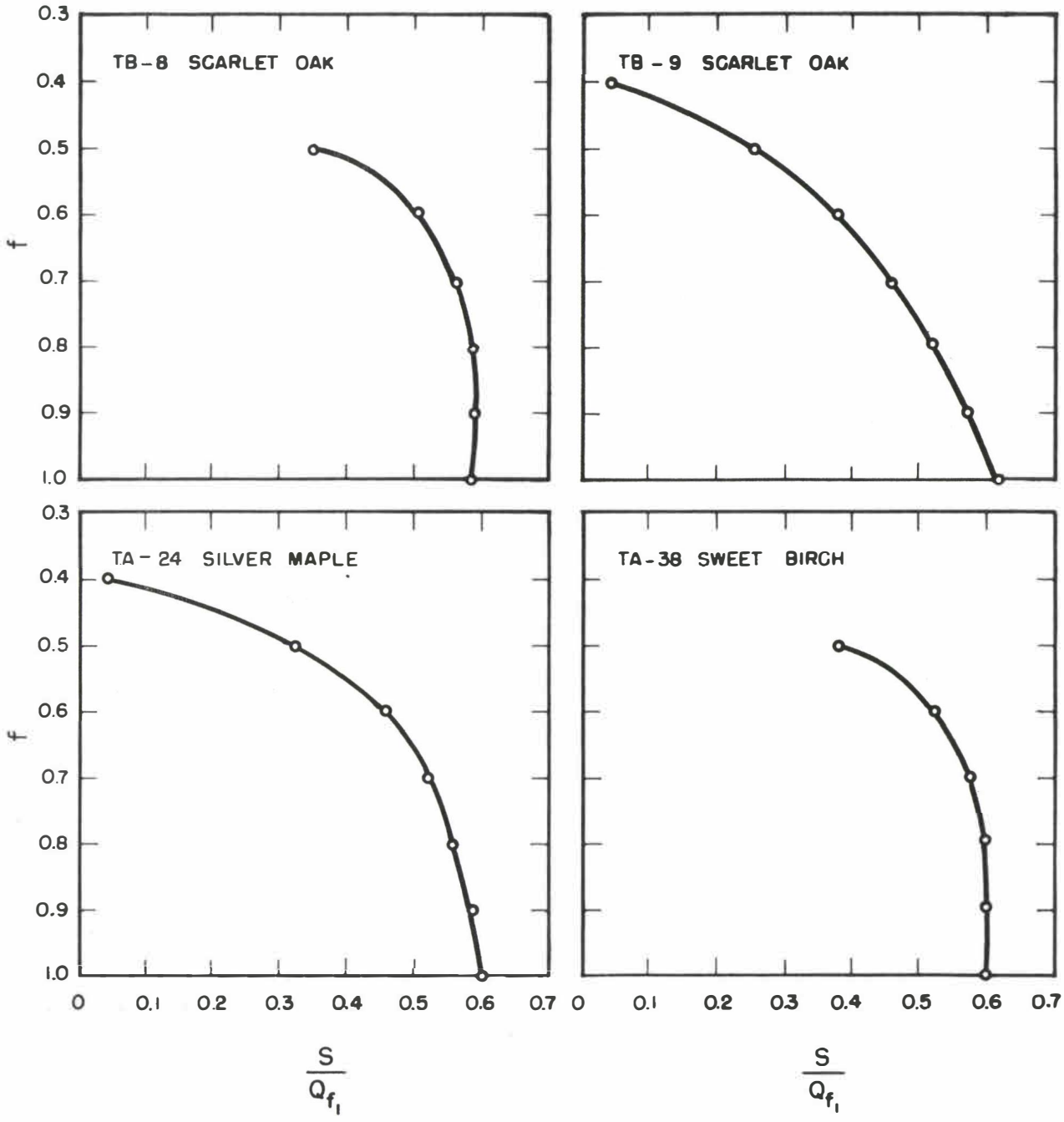

Figure 15.--Typical stress distribution curves at failure for trees breaking (TB-8 and TB-9) and trees uprooting (TA-24 and TA-38)

Table 6.--Summary of statistical tests for homogeneity of sample population

Statistics	By species breaking			By species uprooting					
	S.O.[1/]		Y.P.	S.B.		S.O.	S.B.+ S.O.		P.H.
Mean $\bar{E}_b$	1.551		1.412	1.384		1.290	1.330		1.214
Degrees of freedom	8			5			7		
Mean difference	.139			.094			.116		
Standard error of mean	.340			.508			.452		
Calculated Student's "t"	.409			.185			.257		
Tabular Student's "t" at 5%	2.360			2.571			2.365		

Statistics	By species											
	S.O.		Y.P.	S.O.+ Y.P.		S.B.	S.O.+ Y.P.+ S.B.		P.H.	S.O.+ Y.P.+ S.B.+ P.H.		A.B.
Mean $\bar{E}_b$	1.446		1.212	1.405		1.212	1.607		1.214	1.571		1.105
Degrees of freedom	13			17			19			21		
Mean difference	.234			.193			.393			.466		
Standard error of mean	.316			.310			.393			.252		
Calculated Student's "t"	.740			.622			1.000			1.849		
Tabular Student's "t" at 5%	2.160			2.110			2.093			2.080		

Statistics	Break and uproot failure			Normal and inflected failure		
	Break		Uproot	Normal		Inflected
Mean $\bar{E}_b$	1.409		1.303	1.324		1.421
Degrees of freedom	22			22		
Mean difference	.106			.097		
Standard error of mean	.211			.144		
Calculated Student's "t"	.503			.674		
Tabular Student's "t" at 5%	2.074			2.074		

1/ See key in table 1.

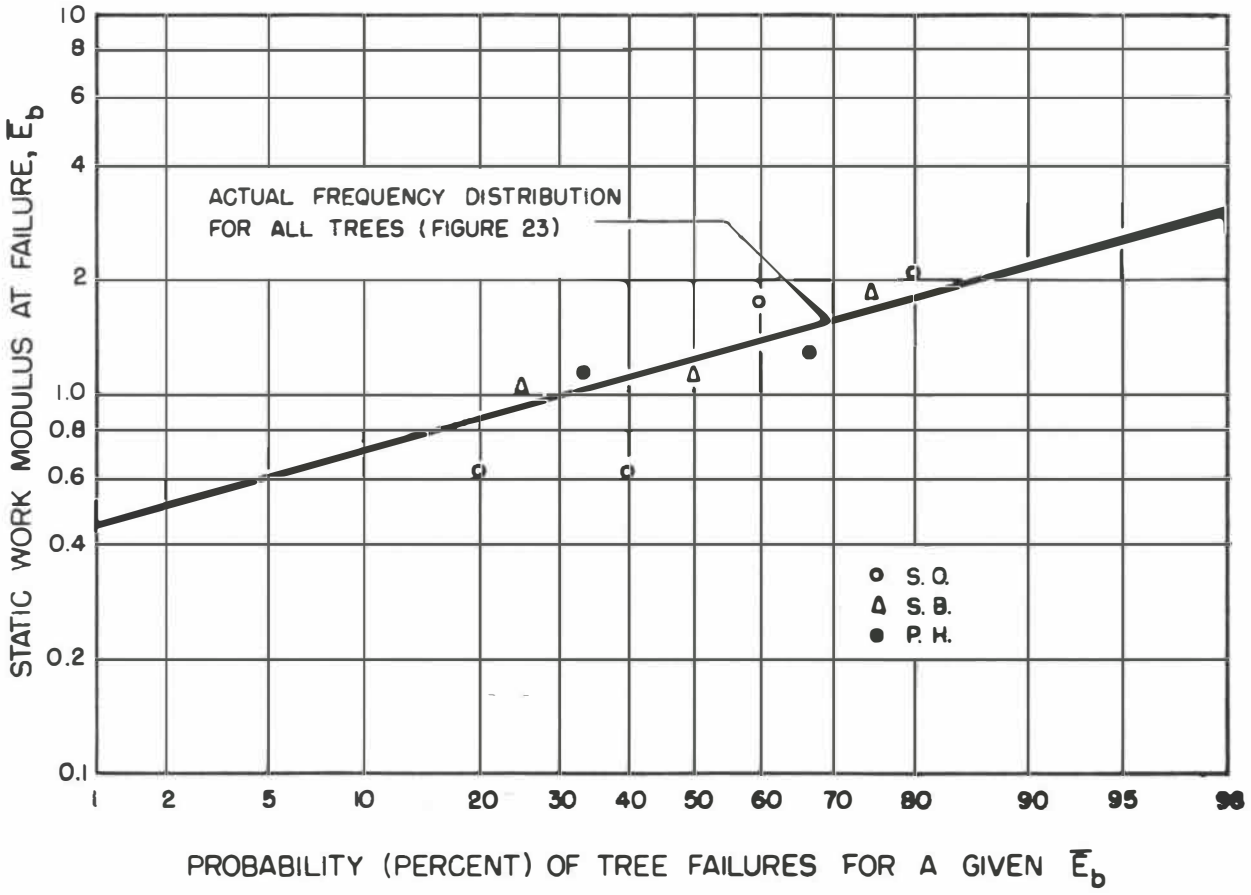

Figure 19.--Actual frequency distribution by species of static work moduli, $\bar{E}_b$, for trees uprooting

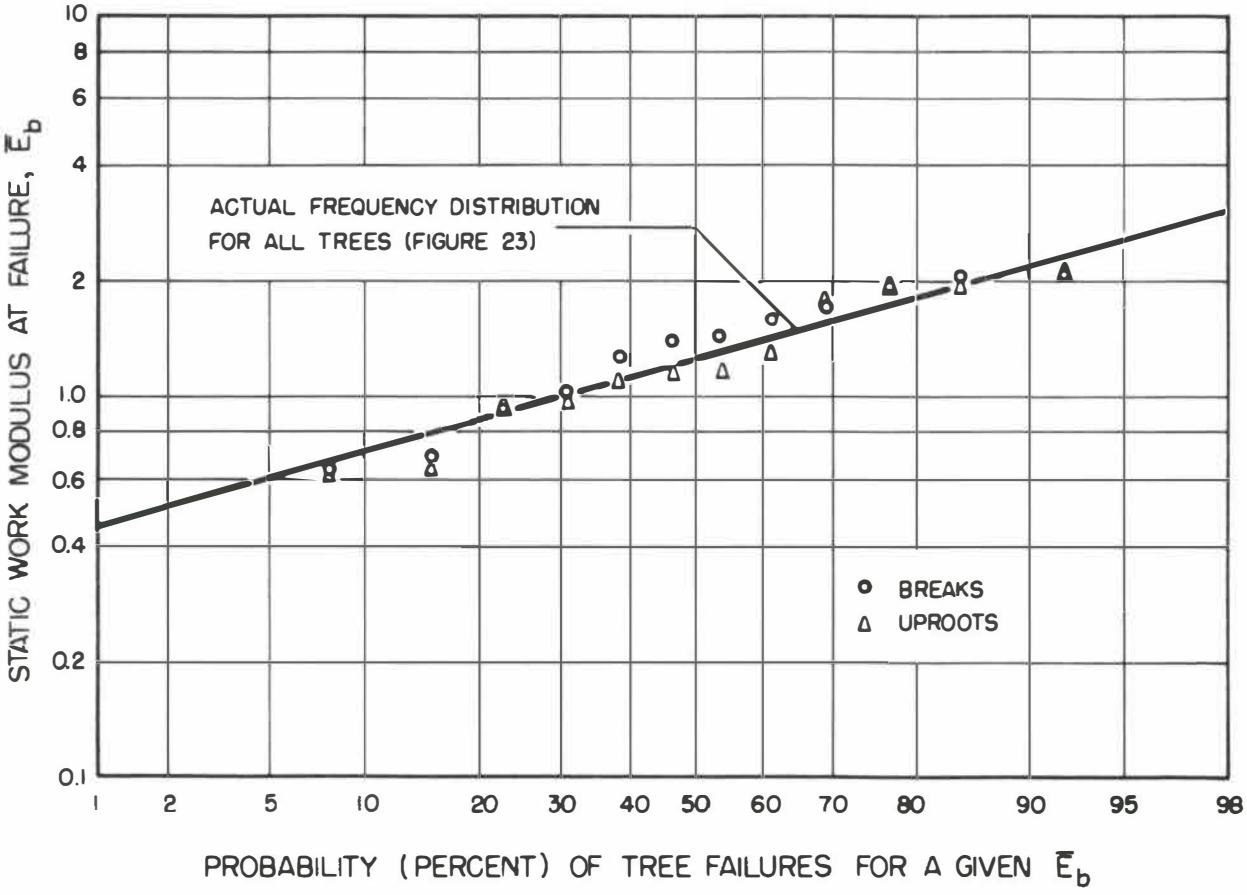

Figure 21.--Actual frequency distribution of static work moduli, $\bar{E}_b$, for breaks and uproots

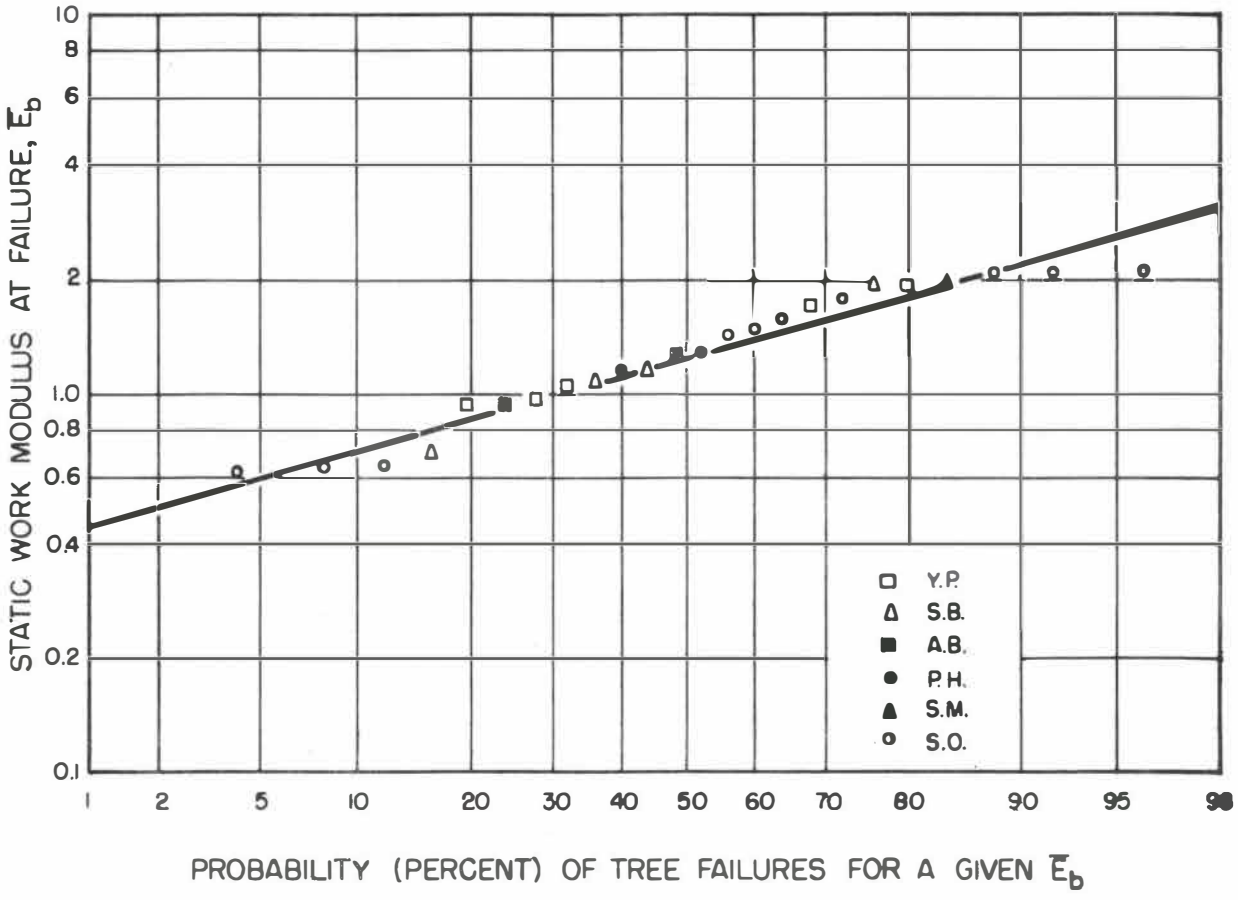

Figure 23.--Actual frequency distribution of static work moduli, $\bar{E}_b$, for all trees tested grouped into one sample population

DISCUSSION OF RESULTS

Because of the heterogeneous nature of wood, considerable variation in strength and other related properties are to be expected. Even when clear specimens are tested, the variation is surprisingly large (16).

When the force-deflection data gathered in this study were plotted, it was found that some of the trees exhibited curves with a definite inflection (figure 9) before failure by breaking or uprooting occurred. In some cases a steady drop in force (figure 10) was recorded before failure. These deviations from the normal type of curves (figures 8 and 11) can be explained in part, if not completely, by the base fixity of the trees in relation to their strength properties.

Fegel (9) who investigated the strength properties of trunk, branch, and root wood in certain northeastern trees, which, incidently, included some of the species studied in this report, found root wood to be much weaker in tension and compression than either trunk or branchwood. His results indicate, however, that root wood stressed in tension was approximately equal in strength to trunk wood stressed in compression. In addition, root wood was found to be approximately twice as strong in tension as it was in compression.

If a force of sufficient magnitude is applied to a tree such that the wood in the stem is stressed beyond the elastic limit, further loading may cause the roots to fail in compression. This was brought out by Mergen (12) in his paper on the mechanics of wind-breakage and windthrow. He emphasized the fact that the roots of a tree which is not firmly fixed at its base would fail in compression on the leeward side before the roots on the windward side are subjected to tension stresses. Depending on the tenacity, distribution, and strength of the roots on the tension (windward) side of the tree, variations in the form of the force-deflection curves can be expected. If the roots are quite firm when stressed in tension, an inflection in the curve will result. Whether the stem uproots or breaks after the inflection depends on the aggregate strength of the roots in comparison to the stem strength. If, on the other hand, the roots are not firm when stressed in tension, excessive root slippage will occur with a subsequent drop in force as the stem uproots. It is interesting to note that a drop in force can also occur when a stem is stressed to breakage. This is a result of compression failures forming along the stem as it is stressed.

It can be seem from the summary presented in table 4 that uprooting failures occurred in all species tested and breakage in all but two, pignut hickory and silver maple. Additional tests would have undoubtedly resulted in breakage failures for these two species also.

Although the method used to calculate the static work modulus does not take into account the energy of inflection exhibited by some of the trees, the $\bar{E}_b$ values presented in this paper have included this energy as part of the static work modulus. This was done after it was found that the energy of inflection was only a small part of the total static work modulus.

From table 6 it is apparent that some species were not included in the various groups segregated for statistical analysis. They were deleted because of a limited sample of trees taken for the various species and the occurrence of single values of $\bar{E}_b$ which could not be statistically evaluated for a specific group. Even with these limitations, however, the results indicate the trees for this study were from a homogeneous population and could be treated as a group.

The actual frequency distribution of the various groups of $\bar{E}_b$ values (figures 18-22) were plotted to determine whether species or type of failure had any affect on the energy level of failure for these groups in comparison to the actual frequency distribution of all trees tested, grouped into one sample population (figure 23). The greatest variance can be seen in figures 18-20, where the energy levels were approximately the same but the range of $\bar{E}_b$ values within a group showed large variations. A major part of these variations can be explained by the limited data collected for the various species. A larger sample would undoubtedly have given much better results.

From figures 21-22 it can be seen that the actual frequency distributions of $\bar{E}_b$ values of the various types of failures varied only slightly, and the energy levels were approximately the same in magnitude. This would seem to indicate that breakage and uprooting, with or without an inflection, require the same amount of energy.

It should be pointed out at this time that even though data for only one silver maple were collected in this study, the data were included in the distribution curve for all trees (figure 23). This decision was based on the value of the static work modulus calculated for this tree, which appeared to be of the same order of magnitude as that for the other species studied (see table 5).

From the frequency distribution curve of $\bar{E}_b$ values presented in figure 23, the energy required to break or uproot any given tree in a site II or better mixed-hardwood forest can be predicted for any probability level. The extent of damage that a site II or better-mixed hardwood forest may sustain for a given energy level can also be predicted. Based on the sample taken for this study, approximately one-half of the failures that will occur in this site-class will be by breaking.

APPENDIX A

EQUIVALENT FORCE AND CHORD-DEFLECTION FOR STATIC BENDING TEST

Table 7 (continued)

Tree No.	Species		Equivalent force R_e (lbs) and chord-deflection y (ft)[1/]										
TA-33	P.H.	R_e	132	253	329	350	359	379	277				
		y	5.8	10.3	13.3	17.1	20.4	23.2	36.6				
TA-24	S.M.	R_e	825	2035	2527	2812	2785	2676					
		y	3.0	6.7	10.2	14.3	16.6	19.7					
TA-8	S.O.	R_e	1259	1655	1846	1795	1994						
		y	5.8	9.9	14.3	16.1	21.1						
TA-9	S.O.	R_e	1369	1643	1879	1969	2143	2395					
		y	4.2	7.1	11.5	15.3	18.6	21.8					
TB-1	S.O.	R_e	495	1010	965	1230	1294	1357	1410	1449			
		y	1.3	3.8	6.0	8.7	11.2	13.8	16.4	20.8			
TB-2	S.O.	R_e	206	610	880	1145	1242	1353	1525				
		y	3.0	6.0	8.4	9.8	12.6	14.9	23.3				
TB-3	S.O.	R_e	190	482	700	1194	1243	1357	1387				
		y	3.0	6.2	10.3	13.6	16.6	20.5	28.6				
TB-4	S.O.	R_e	655	814	1041	1127	1179	1196	1091	1115	1025		
		y	5.5	7.8	10.5	13.3	15.7	22.4	26.6	29.2	39.4		
TB-5	S.O.	R_e	119	155	907	937	985	997	1024	1030	1103	1255	1773
		y	6.0	10.2	14.0	17.0	19.9	22.6	26.1	29.5	33.0	39.0	42.8
TB-6	S.O.	R_e	242	566	733	987	1112	1204	1286				
		y	4.6	6.8	8.3	12.2	14.7	16.5	24.8				
TB-8	S.O.	R_e	523	918	1241	1353	1439	1492	1602	1688	1746	1981	
		y	4.0	7.0	9.8	11.3	13.3	15.5	17.8	20.2	22.5	30.4	
TB-9	S.O.	R_e	421	906	1207	1519	1749	1955	2055	2175	2340	3320	
		y	2.6	5.5	7.4	10.1	13.2	16.3	19.0	21.8	25.6	34.2	

1/ Force and deflection in last column for each tree are values at failure.

Table 8.--Force modulus and deflection modulus for static bending test

Tree No.	Species	Force modulus $\bar{R}$ and deflection modulus $\bar{Y}$ [1]							
TA-14	Y.P.	$\bar{R}$	.172	.296	.483	.559	.624	.669	1.351
		$\bar{Y}$	.256	.429	.608	.717	.717	.981	2.384
TA-29	Y.P.	$\bar{R}$	.085	.303	.463	.558	.529	.701	
		$\bar{Y}$	.265	.492	.769	1.090	1.613	2.189	
TA-34	Y.P.	$\bar{R}$	.137	.242	.485	.538	.576	.598	.645	.630
		$\bar{Y}$	.232	.402	.841	1.073	1.244	1.524	1.720	2.036
TA-35	Y.P.	$\bar{R}$	.302	.594	.792	.823	.812	.887		
		$\bar{Y}$	.456	.975	1.543	1.951	2.321	2.839		
TA-37	Y.P.	$\bar{R}$	.239	.374	.495	.571	.717			
		$\bar{Y}$	.421	.684	.985	1.263	1.954			
TA-23	S.B.	$\bar{R}$	.182	.353	.514	.637	.706	.657		
		$\bar{Y}$	.226	.365	.678	.869	1.086	1.443		
TA-31	S.B.	$\bar{R}$	.318	.349	.564	.643	.661	.676		
		$\bar{Y}$	.186	.457	.728	.983	1.254	2.135		
TA-38	S.B.	$\bar{R}$	.096	.221	.347	.461	.573			
		$\bar{Y}$	.184	.377	.535	.868	2.044			
TA-39	S.B.	$\bar{R}$	.487	.618	.696	.722	.725	.685		
		$\bar{Y}$	.603	.927	1.471	1.854	2.325	2.972		
TA-44	A.B.	$\bar{R}$	.284	.550	.680	.775	.830	.891	.998	
		$\bar{Y}$	.317	.686	.992	1.239	1.504	1.823	2.168	
TA-45	A.B.	$\bar{R}$	.120	.340	.488	.605	.696	.720	.712	.727
		$\bar{Y}$	.143	.591	.743	.968	1.272	1.475	1.670	1.945
TA-22	P.H.	$\bar{R}$	.067	.190	.219	.298	.419	.452	.522	1.550
		$\bar{Y}$	.148	.265	.320	.410	.652	.726	.867	1.683

1/ Moduli in last column for each tree are values at failure.

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NOMENCLATURE

The following nomenclature is used in the paper:

a = constant in stem-form equation

b = constant in stem-form equation

$c = \frac{b}{a}$, stem-form factor

d = diameter along stem inside bark, in.

d_{bh} = stem diameter at breast height, in.

d_i = stem diameter inside bark at breast height, in.

E = modulus of elasticity, lbs/sq. in.

$\overline{E}_b$ = static work modulus at failure

$f = H/H_{bh}$, fractional height of stem measured from top of stem downward

f_{br} = position of stem breakage

f_m = position of maximum stress

f_l = position of loading

H = height of stem measured from top of stem downward, ft

H_{bh} = height of stem above breast height, ft

H_{cp} = height of stem above breast height to loading point, ft

H_o = total height of tree from ground, ft

I_i = moment of inertia inside bark at breast height, in.

k_a = actual restoring force constant, lbs/ft

k_r = theoretical restoring force constant, lbs/ft

L = moment arm

$\overline{K} = k_a/k_r$, restoring force constant modulus

MR = modulus of rupture, lbs/sq in.